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ARCHITECTURAL DESIGN CONSIDERATIONS FOR A ROBOTIC POWER INFRASTRUCTURE ON THE MOON

Raul Polit-Casillas¹ raul.polit-casillas@jpl.nasa.gov, John Elliott¹

Alex Austin¹, Scott Howe¹, Aaron Parness¹, Brent Sherwood¹, Miles Smith¹, Gerald Voecks¹, Anthony Colaprete⁵, Terry Fong⁵, Sandra Magnus³, Phil Metzger⁶, Harrison H. Schmitt³, Michael Sims², Kris Zacny⁴

¹NASA Jet Propulsion Laboratory, California Institute of Technology, USA

²Ceres Robotics, USA

³Consultants, USA

⁴Honeybee Robotics, USA

⁵NASA Ames Research Center, USA

⁶University of Central Florida, USA

Abstract

The development of a permanent robotic base on the Moon, requires multiple considerations, such as infrastructure, habitat design, operational schemes and robotic construction techniques, in order to take advantage of the presence of water ice. Within the complexity of such a challenge, the design of a power infrastructure capable of addressing autonomous robotic deployment and operations is key. This paper presents relevant findings regarding an ongoing research activity at the Jet Propulsion Laboratory to understand, define and design a new type of architecture for a modular power infrastructure. Such infrastructure is part of scalable robotic base concept that takes into account both architecture and operations standpoints. Complementary papers to this describe other systems such as habitats, ISRU schemes, etc. This research effort was centered on the constraints, preliminary requirements and concept designs for a novel approach that uses solar power as a primary energy source, and nuclear power for emergency needs. Some of these points include overall architecture strategies, deployment and location schemes, as well as modular multifunctional schemes for scalability and maintenance purposes. Multiple trades were developed addressing these key assumptions, and parametric models were created making the most of the state-of-the-art computational design and advanced manufacturing techniques for robotic systems (e.g., additive manufacturing or composites). Finally, detailed concept designs and parametric CAD / BIM models are presented in order to better understand integration, expandability and operations of the this architecture. These models are meant to be used as an ongoing and expandable reference set for future studies regarding modular robotic bases on Moon and other planetary surfaces in the 21st century.

Keywords: moon, habitat, base, power, infrastructure, robotic

Acronyms/Abbreviations

Robotic Lunar Surface Operation (RLSO), In Situ Resource Utilization (ISRU), Computer Aided Design (CAD), Building Information Modelling (BIM), regenerable fuel cells (RFG) Permanent Shadow Region (PSR), Partially Lit Region (PLR), One Degree of Freedom (DOF), Beginning of life (BOL), End Of Life (EOL).

1. Introduction

The first Robotic Lunar Surface Operations (RLSO) report [1] was elaborated by the Boeing Company and NASA's Ames Research Center (ARC) in 1990 as a way to understand the operational aspects of a robotic base on the moon. Taking into account available data and what was considered at the time near-term state-of-the-art technologies, the report made an emphasis on surface operations, construction techniques and solar energy, as well as robotic and base elements (e.g., habitats). This second study inherits the same spirit of the previous

effort, developing an update for the 21st century that takes into account both current state-of-the-art technologies, and data science standpoints. The RLSO2 [2,3,4] study tackles several fields such as: lunar robotic construction and base elements [5], power infrastructures, lunar base architectures and ISRU [6], and operation models [7]. This second time, the approach not only provides an updated screenshot of such an endeavour, but furthermore a solid foundation towards the creation of models (e.g. CAD, BIM for Aerospace [8], Operations) which can be later used, updated and upgraded by the technical community across fields.

1.1 Deployable Infrastructure Precedents

The use of deployable structures has been present in many fields over the last decades, such as military and emergency shelters, temporary structures on Earth [9], as well as concepts for planetary surface and orbital habitats [10]. Orbital structure examples developed at JPL include Starshade [11] (figure 1) and concepts for deployed

habitats [5] developed for RLSO2 as described in figure 2. Among the many types of deployable structures, the use of truss-like structures and tensegrities (compression-tension systems) are especially interesting due to their efficiency in terms of mass. These types, due to reliability and extensive use on Earth, were selected as the primary approach towards designing the structural deployments.



Figure 1. Starshade deployment at JPL (NASA/Caltech).



Figure 2. Deployable barrel vault for RLSO2. JPL (NASA-Caltech).

Deployable structures such as these, for both terrestrial and space applications, present high compactability and low density.

1.2 Previous Planetary Surface Power Systems.

Lunar surface concept bases, as well as other planetary surface deployment concepts, developed over the years in the literature, have presented both solar and nuclear power options. The original RLSO base introduced a solar power architecture using solar towers as shown in figure 3. This infrastructure was conditioned by the location of the base as well as the launch/landing scheme. Photovoltaic panels were complemented by the use of regenerable fuel cells (RFC). Other precursor concepts for lunar infrastructure show fission nuclear

reactors [11] as the main power scheme. This is the case of the study conducted by JPL in 2015 to assess the use of the Prometheus reactor based power generator for the lunar environment, see figure 4.

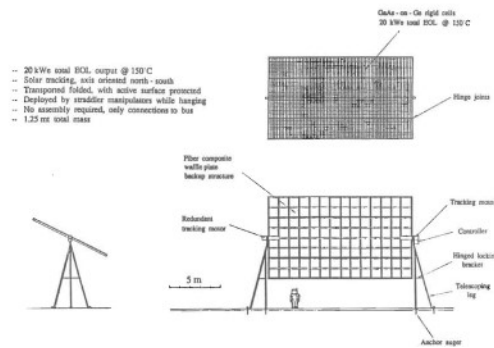


Figure 3. Freestanding photovoltaic array structure for 20 kWe, Sherwood [1].

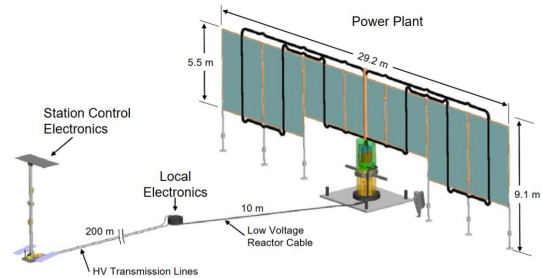


Figure 4. Lunar Fission Surface Power System Design, JPL 2015.

The number of concepts following solar, nuclear or hybrid schemes is large in the literature, setting as a conclusion the need of a solid but also adaptable power architecture in order to address present and future requirements for a moon base.

2. Preliminary Requirements

For the development of an architectural approach for such robotic base, certain preliminary requirements were set as starting points in the design process. These requirements should only be considered as an initial goal towards generating CAD, BIM and operational models that could be tweaked later on.

2.1 Base Power Needs

For the current baseline, the base would be served with 4 flights per year, or in other words one flight per 3 lunar days. So as a bounding case this represents $T_1=1,008$ (1) hours per cycle as it follows: $T_1 = 3 \text{ cycles} \times 14 \text{ days/cycle} \times 24 \text{ hours/day} = 1,008 \text{ hours}$.

The baseline design of the RLSO2 base includes the following activities and systems, as a breakdown of the initial equipment and activity assessment for the power needs:

- Base elements
 - Habitat facilities
 - Habitat module (Occupied)
 - Workshop module (Un-occupied)
 - Base Operations including
 - Construction systems (including robots)
 - Telecommunication Array
 - Propellant Storage (for ISRU as well)
- ISRU
 - Excavation
 - Resource Hauling
 - Purification
 - Extraction
 - Electrolysis

Regarding the ISRU energy process, the estimated energy cost to process 1 Kg of water is approximately 10.8 kWh. The energy cost of 40,000 kg of propellant is 432,000 kWh, assuming a ratio of 6:1 of Oxygen to hydrogen for the engines. This means 2.2 MWh of energy is required for ISRU per year, which considering T_1 it means around 550 kW per cycle. ISRU energy assumes half time.

Table 1 shows a detailed description of the energy needs, however this requirement was summarized to a

Table 1. ISRU and Base energy requirements [6]

ISRU Energy	Power (kWh/kg H ₂ O)	Energy/year (kWh)
Excavation	0.2	41,200
Resource Hauling	0.17	35,041
Purification	0.01	2,060
Extraction	2	412,000
Electrolysis	6.5	1,339,000
Liquefaction	1.9	399,125
Total		2,228,426
Other Energy		
Habitat	30	262,800
Human Hab (occupied)		
Workshop (un-occupied)		
Base Operations	2	17,520
Construction systems		
Telecommunications		
Fuel Storage	4	35,040
Total		315,360
Total energy/year (kWh)		2,543,786
Instantaneous energy system power assuming "other energy" is full-time and "ISRU Energy" is half- time (kW)		545

round number of 500 kW in order to start the design process. These model can be scaled up or down later on.

2.2 Structural requirements

The approach taken for the RLSO2 base sets a series of mechanical open requirements for the structure that could be summarized as follows:

- To be as light-weighted as possible.

- Stowed configurations should fit within a 4.5 m diameter of the launcher fairing
- To minimize the number of mechanisms.
- Mechanism should be able to operate in the lunar environment.
- Use a modular approach for future robotic maintenance and upgrades.

As such, all power infrastructure components requiring deployment and transport should also comply with the following design requirements:

- All system should be compatible with the mobility and construction RSLO2 infrastructure including robotic manipulation, operations, and transport systems.
- All system should be capable of self-deployment and stowage for easier autonomous operations.

2.3 Lunar Environment

The lunar environment presents some unique and challenging conditions in comparison with Earth or other planetary surfaces. The RLSO2 base would located near the polar areas providing a subset of specific environmental conditions. The most relevant lunar environment characteristics [14] taken into account for these concept and model development include:

- Gravity is 1.62 m/s²
- Radiation environment should be considered
- Avg. Temperature range: -233°C to 123°C
- Seismic Energy is approx. 2×10^{10} J/yr

3. Architecture Design Approach

Previous points set up both environmental conditions as well as technical requirements and heritage. Once that has been established, the final development of a power architecture infrastructure for RLSO2 is based on a series of architectural assumptions and requirements.

3.1 Architecture assumptions

The power infrastructure approach for RLSO is mainly solar, with a nuclear reactor as a potential emergency backup. Basic architecture elements would include, among others: [a] photovoltaic towers, [b] power transmission units (cable and/or laser), [c] power storage units, [d] robotic power charging units, [e] emergency power units. Clusters of photovoltaic towers should be relocatable, providing at least an average of 0.5 MW (500KW). As per landing strategies, the design approach is that each power unit should require a minimum number of landings, leveraging self-deployment and easy transport and maintenance by the base robotic systems.

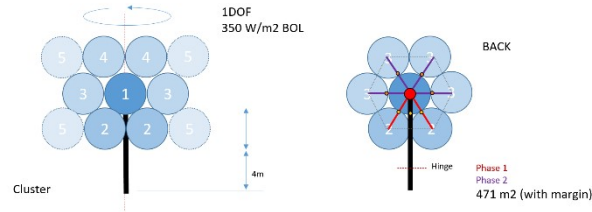
3.2 Urbanism and locations

The location of the RLSO base would be in the South Polar Regions within two types of solar conditions: [a]

4.1.1 1 - Ultraflex Grape

Any of the following architecture families aim to reduce complexity and mass while improving reliance and maintainability (see Figure 10).

Mega-flex architecture (Grape) – F1



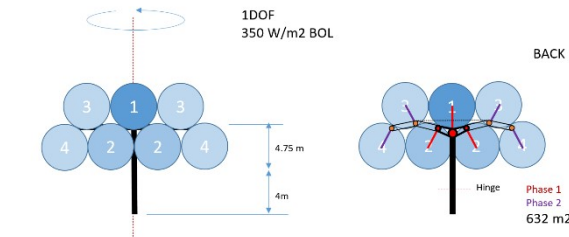
● = 68 m² (Rad 4.75 m) - 5% Margin
1300 m² → ≥ 19 Arrays → ≥ 3 Clusters
10⁴5 m² Ops → ≥ 3 Clusters → 33000 m² influence (104 m radius)

Figure 10. F1 Ultraflex Grape Scheme.

4.1.2 F2 – Ultraflex Zig-Zag

This family deploys megaflex around a central deployable horizontal spine, see figure 11.

Mega-flex architecture (Zig-Zag) – F2



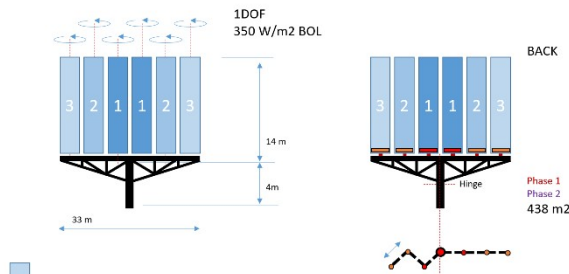
● = 68 m² (Rad 4.75 m) - 5% Margin
1300 m² → ≥ 19 Arrays → ≥ 3 Clusters
10⁴5 m² Ops → ≥ 3 Clusters → 33000 m² influence (104 m radius)

Figure 11. F2 – Ultraflex Zig-Zag scheme

4.1.3 V1 – Vertical ROSA

Vertical architectures allow to have one single mechanism to control the DOF, see figure 10.

ROSA Architecture Vertical – V1



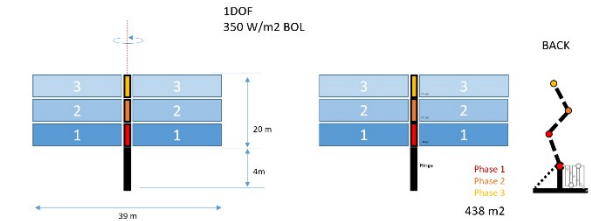
■ = 77 m² (5.5 x 14 m) - 5% Margin
1300 m² → ≥ 18 Arrays → ≥ 3 Clusters
10⁴5 m² Ops → ≥ 3 Clusters → 33000 m² influence (104 m radius)

Figure 12. V1 – Vertical ROSA Scheme

4.1.4 H1 – Horizontal ROSA

This architecture presents an articulated central vertical spine, deploying arrays on both sides (figure 13).

ROSA Architecture Horizontal – H1



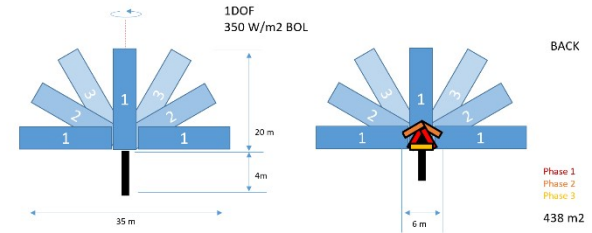
■ = 77 m² (5.5 x 14 m) - 5% Margin
1300 m² → ≥ 19 Arrays → ≥ 3 Clusters
10⁴5 m² Ops → ≥ 3 Clusters → 33000 m² influence (104 m radius)

Figure 13. H1 – Horizontal ROSA scheme

4.1.5 A1 – Angled ROSA

An angle approach allows to reduce the amount of deployment mechanism and structural components, but casts more shadows. See figure 14.

ROSA Architecture Angle – A1



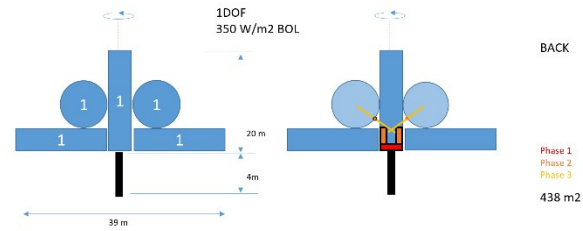
■ = 77 m² (5.5 x 14 m) - 5% Margin
1300 m² → ≥ 19 Arrays → ≥ 3 Clusters
10⁴5 m² Ops → ≥ 3 Clusters → 33000 m² influence (104 m radius)

Figure 14. A1 – Angled ROSA scheme

4.1.6 Y1 – Hybrid Ultraflex plus ROSA

The hybrid family, combines ROSA and Megaflex deployments. Figure 15 only shows a potential design among many others.

ROSA Architecture Hybrid – H1 ?



■ = ~88 m² (5.5 x 16 m) - 5% Margin
● = ~95m² (Rad 5.5 m) - 5% Margin
1300 m² → ≥ 7 Combined Arrays → ≥ 3 Clusters
10⁴5 m² Ops → ≥ 3 Clusters → 33000 m² influence (104 m radius)

Figure 156. Y1 – Hybrid Megaflex plus ROSA scheme

4.3 A1 Angled Architecture

As a result the first CAD study was conducted on the angled architecture (figure 19). This approach reduced the number of actuators and supporting structure but as a drawback it creates some small shadow areas on the solar arrays. The central structure is mounted on a rotating platform. Under such platform, systems such as batteries or fuel cell can be added with a modular approach. Six ROSA arrays are stowed within the central structure, and only 4 of them need to be partially rotated

in order to be deployed. All deployments use rotational move actuators for simplicity and reliability. The structure uses composite tubes and metal end fittings to create a very lightweight truss-like structure. Each ROSA array is 6x15 meters when deployed, furthermore all of them are above 4 meters from the ground. The core structure is on top of a rotating platform offering 1 DOF. The stowed assembly (figure 19, top right), can be transported and handled by the RLSO2 robotic mobile gantry [5].

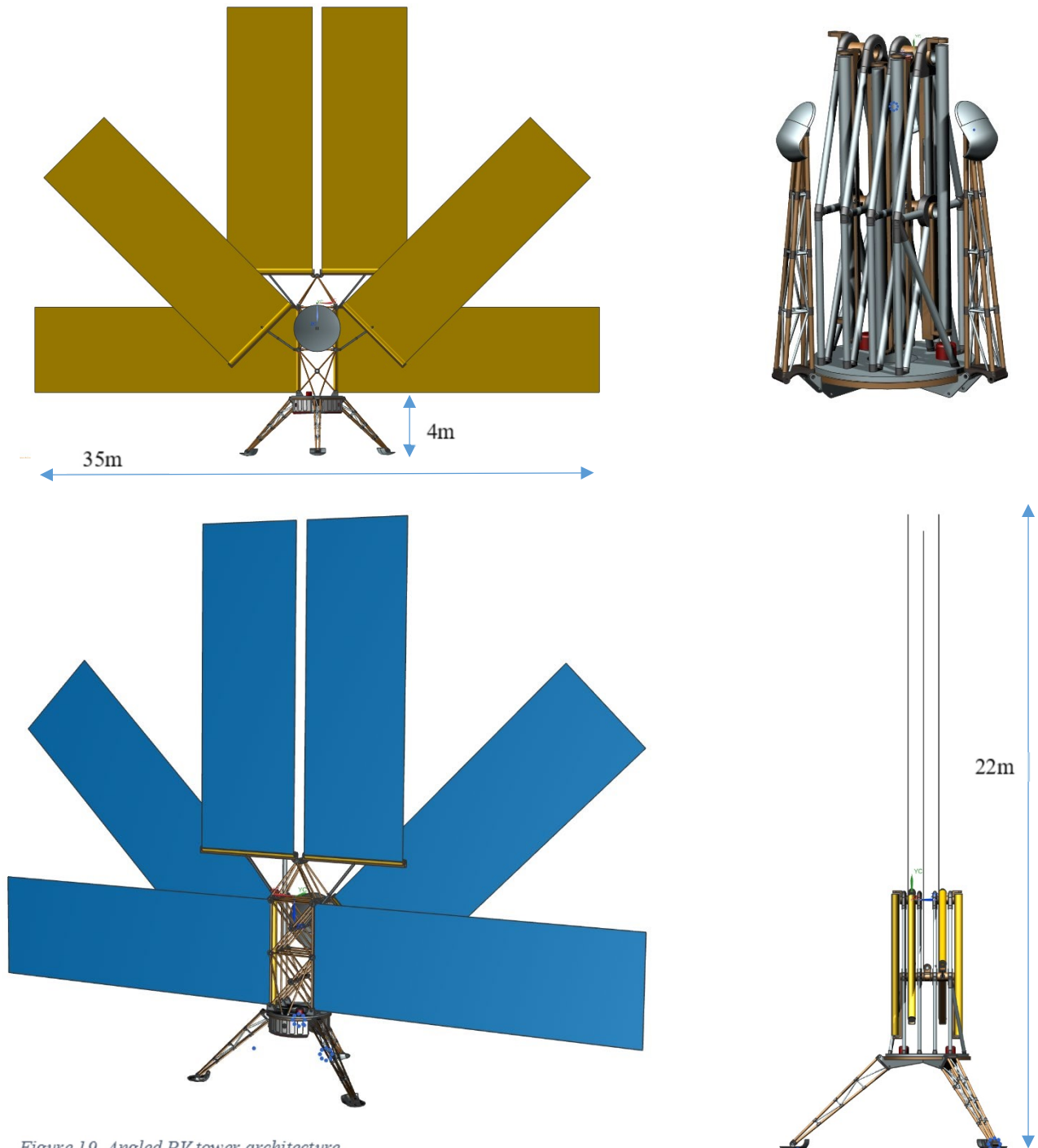


Figure 19. Angled PV tower architecture.

4.4 H1 Horizontal - Final Architecture

Among all the architectures studied during the first design phase of the RSLO2 study, the horizontal approach for the PV tower was selected as the final one. This one essentially follows the same design principles described for the angled architecture (figure 20), however the vertical deployment of the central boom is done using a zig-zag configuration. The central aluminium structure

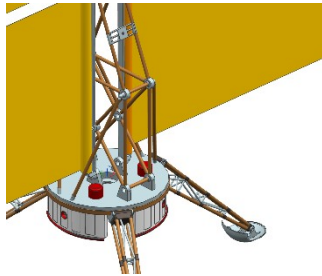


Figure 20. Left. Perspective shows the central structure of the tower.

Figure 21 shows an initial concept mass equipment list (MEL), for the generic structural elements of this tower. This assumes lightweight composite tubes and metallic connectors. A complete 3D model of the stowed horizontal deployment tower is shown in figure 22. All systems can be added modularly to the bottom of the rotating platform including batteries, electronics, fuel cell and cable connections, etc.

RLSO Power PV Outpost									
Apr-19									
	%	Units	Mass (CBE) [Kg]	CBE Total [kg]	Contingency [%]	CBE + Cont	Component Total [Kg]	Total [kg]	
Structure									
Main Structure	27							1096.253	
Rod 1		24	7	168	15	193.2	193.2		2486.62
Rod 2		32	4	128	15	147.2	147.2		
Rod 3		4	8	32	15	36.8	36.8		
Node 1		26	2.5	65	30	84.5	84.5		
Node 2		8	3.7	29.6	30	38.48	38.48		
Node 3		8	2.7	21.6	30	28.08	28.08		
Platform		1	150	150	30	195	195		
Harnessing (10% Total)							248.662		
Bolts, etc. (5% Total)							124.331		
Rotating Mechanism	3.9							156	
Protating Platform Support		1	30	30	30	39	39		
Platform Ring		1	60	60	30	78	78		
Rotating Mechanism		2	15	30	30	39	39		
Arrays	61							2431.7	
Rosa (5.5x16 m, 88 m2)		6	300	1800	15	2070	2070		
Vertical Support Assy		4	6	24	15	27.6	27.6		
Horizontal Support Assy									
Central Hinge		1	10	10	30	13	13		
Array Support		2	40	80	30	104	104		
Arm		2	13	26	30	33.8	33.8		
Bottom Hinge		1	5	5	30	6.5	6.5		
Angle Suport Assy									
Central Hinge		2	10	20	30	26	26		
Array Support		2	40	80	30	104	104		
Arm		2	13	26	30	33.8	33.8		
Bottom Hinge		2	5	10	30	13	13		
Legs	8							322.328	
Base		1	20	20	30	26	26		
Rod1		4	11	44	31	57.64	57.64		
Nodes		12	0.7	8.4	32	11.088	11.088		
Small Rods		5	4	20	33	26.6	26.6		
Foot		3	50	150	34	201	201		
Total								4006.281	

Figure 21. Table. Concept mass equipment list (MEL). JPL.

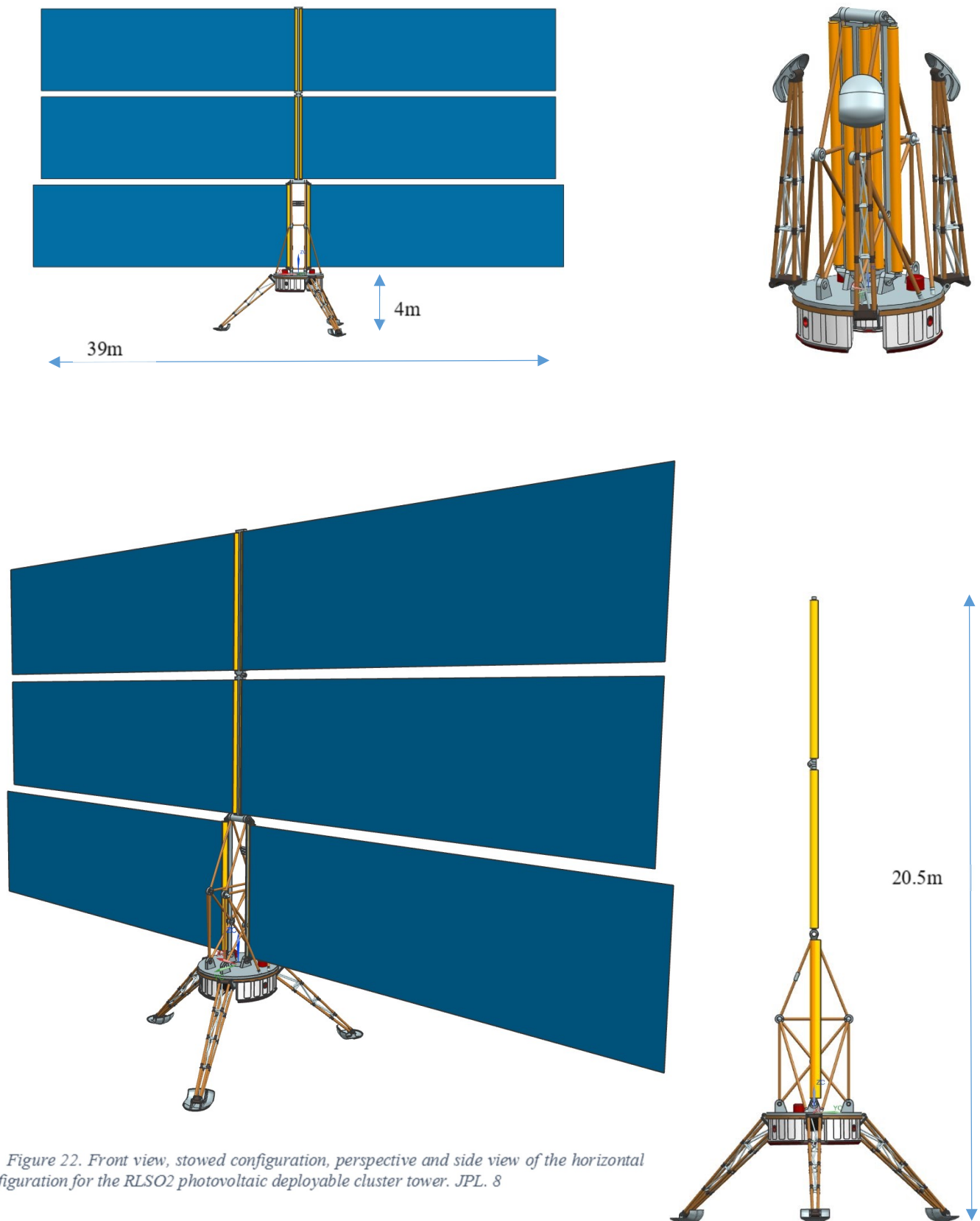


Figure 22. Front view, stowed configuration, perspective and side view of the horizontal configuration for the RLSO2 photovoltaic deployable cluster tower. JPL. 8

4.5 Launch Configuration

The stowed assembly fits within a 4.5 m diameter fairing as figure 23 shows. Bigger launcher fairing diameters, such as those enable by NASA SLS, etc. will enable other simultaneous launching configuration for multiple towers.

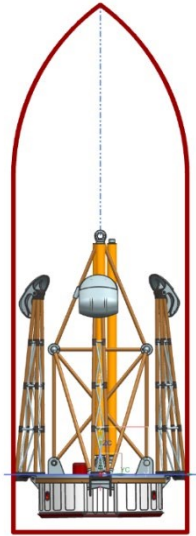


Figure 23. 4.5 meter fairing launch configuration.

4.6 Deployment Approach

As mentioned the stowed assembly (figure 18, top right), can be handled by the RLSO2 crane [5], described in figure 24. This includes transport and placement. Once the tower is deployed vertically on the ground, the three actuated legs can stand up the platform through their unfolding. The feet are design not only to transfer the load into the lunar regolith but also to allow the relative sliding required. The three legs also serve a leveraging tripod, adapting to multiple ground topologies (figure 18, bottom right).

There is also the potential that the solar array towers could be delivered by future commercial landers with approximately 4,000 kg payload capacity, in development by a number of companies. This could enable a flexible infrastructure to efficiently deliver more power units as the base expands.

4.7 Robotic Maintenance

While this topic requires a much more detailed study, the general approach is that all mechanical actuators will design for a fast replacement using a plug&play approach, so robotic manipulators can change the most complex and active subsystems parts.

4.8 Emitter and Power Units

How to transfer energy from the photovoltaic cluster tower to the base is part of an ongoing research and

subsequent paper. However, there are two possible architectures to transfer the power to the base from the multiple locations these cluster towers could be located at. The overall approach is that the structural design allow to use both wired and laser wireless power transfer systems. In both cases the power architecture of the base conducts the energy towards an emitter that transfer the energy to a receptor in the vicinity of the base.

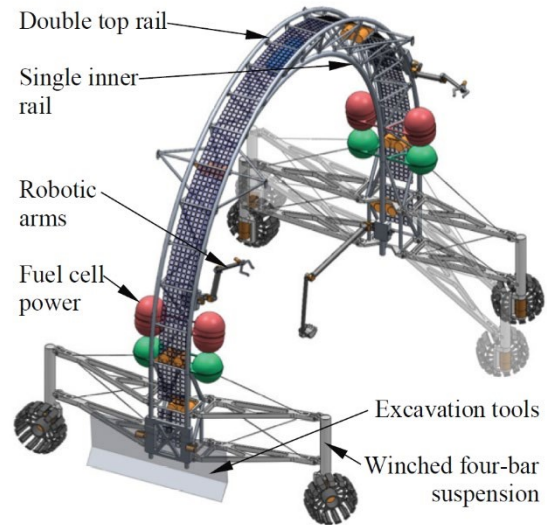


Figure 24. RLSO2 Robotic multiuse crane. JPL. Howe et al. [5]

4.9 Building Information Modeling (BIM)

As part of the design process, detailed parametric mechanical CAD models were created so they could be imported into BIM models of the base in order to perform urbanism, regolith movements, solar and infrastructure studies, besides regular engineering detailing (figure 25).

5. Conclusions

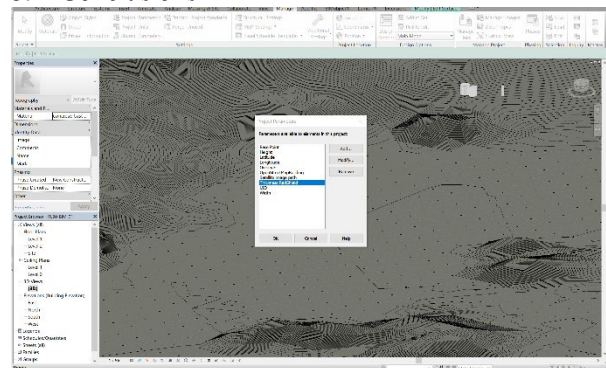


Figure 25. BIM model baseline for RLSO2.

Current state-of-the-art design and manufacturing techniques allow to rethink the original design of the first RLSO robotic base under the light of a highly adaptable architecture approach. This early design studio enables us to think into a different type of highly

portable power network infrastructure for the lunar surface, making deployment, operations and launch easier and more efficient from the robotic operations standpoint. How to capture, transfer and store energy will be a key aspect in future lunar developments.

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